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We retrieve seismic velocity variations within the Earth's crust in the region of L'Aquila (central Italy) by analyzing cross-correlations of more than two years of continuous seismic records. The studied period includes the April 6, 2009, M_W 6.1 L'Aquila earthquake. We observe a decrease of seismic velocities as a result of the earthquake's main shock. After performing the analysis in different frequency bands between 0.1 and 1 Hz, we conclude that the velocity variations are strongest at relatively high frequencies (0.5-1 Hz) suggesting that they are mostly related to the damage in the shallow soft layers resulting from the co-seismic shaking.

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1. Introduction

On April 6, 2009 a M_W 6.1 earthquake struck the central Apennines region near L'Aquila (Italy) causing severe damage and more than 300 fatalities [*Scognamiglio et al.*, 2010]. This area had been long recognized as seismically active [see the official seismic hazard map of Italy, *MPS Working Group* , 2004] and an occurrence of a strong earthquake in the central Apennines could not be considered as totally unexpected. Before the main shock, an increase in the rate of seismicity started on September 2008 and many small size events (about 300 with $M_L \leq 2.5$) occurred beneath the L'Aquila city area. This foreshock sequence culminated with a $M_L = 4.1$ earthquake on March 30, 2009. In the following days, the seismicity decreased until two earthquakes ($M_L = 3.9$ and $M_L = 3.5$) occurred just a few hours before the L'Aquila main shock. In agreement with the extensional tectonics of the central Apennines, the focal mechanism of the L'Aquila earthquake has been determined to be a normal fault on a South-West dipping plane with the rupture area of ~20x15 km^2 and the dipping angle of about 50 degrees [*Cirella et al.*, 2009]. The main shock was followed by an aftershock sequence that included 33 earthquakes greater than $M_L = 4$.

In this study, we use a recently proposed monitoring technique based on ambient seismic noise. The idea of this method is to use signals reconstructed from repeated cross-correlations of continuous seismic records as virtual seismograms generated by highly repeatable sources. In case of well distributed noise, the reconstructed virtual sources are close to point forces and the cross-correlations functions can be considered as Green functions [e.g., *Weaver and Lobkis*, 2001; *Shapiro and Campillo*, 2004; *Sabra et al.*, 2005;

Shapiro et al., 2005]. Highly accurate temporal monitoring can be also performed even with inhomogeneous noise sources distributions when a perfect reconstruction of the Green function is not achieved [e.g., *Hadziioannou et al.*, 2009]. The changes of the travel times measured from the noise cross-correlations reflect variations of the elastic properties in the propagating media, i.e., in the Earth's crust. This approach has been recently applied to monitor active volcanoes [e.g., *Sens-Schönfelder and Wegler*, 2006; *Brenguier et al.*, 2008a; *Duputel et al.*, 2009; *Mordret et al.*, 2010] and large seismogenic faults [e.g., *Wegler and Sens-Schönfelder*, 2007; *Brenguier et al.*, 2008b; *Chen et al.*, 2010] and to detect seasonal changes in the Earth's crust resulting from thermoelastic variations [e.g., *Meier et al.*, 2010].

In a seismogram or in a correlation function, the delay accumulates linearly with the lapse time when the wave speed changes homogeneously within the medium. As a consequence, a small change can be detected more easily when considering late arrivals. This makes the use of coda waves particularly suited to measure temporal variations. This can be done either by using the so-called stretching technique [e.g., *Wegler and Sens-Schönfelder*, 2007] or with a method that was initially developed for repeated earthquakes (doublets) by *Poupinet et al.* [1984]. Here, we use this latter approach that has **been** specifically adopted to make measurements from the noise cross-correlations [e.g., *Clarke et al.*, 2011]. We apply this method to two years of continuous recordings by three seismic stations located in the vicinity of the L'Aquila main shock fault (Figure 1) to measure variations of crustal seismic velocities caused by this earthquake.

2. Selecting and pre-processing the data and computating cross-corelations

Istituto Nazionale di Geofisica e Vulcanologia (INGV) operates two large seismological networks: the Italian National Seismic Network (INSN) and the Mediterranean Very Broadband Seismographic Network MedNet. The INSN consists of more than 250 stations with various characteristics [*Amato and Mele*, 2008]. MedNet consists of 22 very broadband stations distributed over the Euro-Mediterranean area with 13 of them located in Italy [*Mazza et al.*, 2008]. During period of interest for our study, four broadband stations operated in continuous mode within a radius of 25 km from the main shock epicenter. However, records of one of these stations contained too many gaps and we finally decided to use three stations: CAMP and FIAM from INSN and AQU from MedNet (Figure 1). The longest period of data availability at these three stations was between March 27, 2008 and April18, 2010.

We re-sampled time series recorded at the three stations in order to get a perfect time synchronization and filled existing small gaps via a linear interpolation. Then, we pre-processed the vertical component seismograms by whitening their spectra between 0.1 and 1 Hz and by normalizing their amplitude through a one-bit normalization. In this way, the contributions arising from strong transient phenomena were reduced in both time and frequency domains [e.g., *Bensen et al.*, 2005; *Brenguier et al.*, 2008b]. Finally, we computed cross-correlations between the three pairs of stations for every hour of the available recordings.

3. Measurement of seismic velocity variations

We adopted the Multi Window Cross-Spectrum (MWCS) analysis [e.g., *Clarke et al.*, 2011]. This technique was first proposed by *Poupinet et al.* [1984] for retrieving the relative velocity variation between earthquake doublets. *Brenguier et al.* [2008a, b] applied this technique to the cross-correlations of the seismic noise. The main idea of the method is that the noise cross-correlations computed from subsequent time windows can be analysied similar to records from earthquake doublets. When analyzing long time series, we compare a single reference cross-correlation with many subsequent current functions. The reference cross-correlation CC^R for a particular station pair is obtained from stacking all available cross-correlations for this pair and, therefore, is representative of the background crustal state. The current cross-correlations CC^C are obtained from stacking a small sub-set of cross-correlations representative of a state of the crust for a given short period of time. There is a trade-off between the length of the stack required to have stable estimates of the CC^C and the time resolution for detecting the variations. To find an optimal stacking duration for the current function we tested different lengths between 10 and 100 days. For each tested stacking length, we computed all possible functions CC^C by applying moving windows shifted by two days. Then, we computed the correlation coefficient r between the reference function CC^R and every CC^C. The distribution of r characterizes the similarity between CC^R and CC^C for a given stacking length. We represent the overall degree of similarity by the mean and the standard deviation of this distribution. Figure 2 shows these parameters for the three station pairs. We observe that the degree of similarity increases rapidly for short stacking durations and then it tends to stabilize. We selected a value of 50 days as stacking length for computing the current correlation functions.

The MWCS analysis consists of two computational steps [e.g., *Clarke et al.*, 2011]. In the first step, we estimate for a station pair k delay times δt_i^k between CC^R and CC^C within a set of time windows centered at t_i. In case of uniform velocity perturbations, the measured delays δt_i^k are expected to be a linear function of time t_i with a slope corresponding to the relative time perturbation:

$$\frac{\Delta t}{t} = -\frac{\Delta v}{v} \tag{1}$$

where $\frac{\Delta v}{v}$ is the relative uniform seismic velocity perturbation that can be estimated in the second step from a single station pair k via linear fitting of the following equation:

$$\delta t_i^k = -\left(\frac{\Delta v}{v}\right)_k \cdot t_i \tag{2}$$

In order to obtain one estimates representative of the entire crustal volume, we merged together the delays δt_i^k measured from the three station pairs before proceeding with the second step of the analysis. We computed the median value $\widetilde{\delta t_i}$ of the delays δt_i^k for every i-th window, and we inserted it into (2) to estimate of $\frac{\Delta v}{v}$ for the entire region encompassed by the three stations. When performing this analysis, we removed the central part of the cross-correlations containing direct waves (group velocities faster than 2.5 km/s; see Table 1) because they may be sensitive to the changing position of the noise sources [e.g., *Froment et al.*, 2010]. Relative velocity variations were then computed by taking into account the coda of the cross-correlation up to a length of 60 s where the signal decreases to values close to the noise level.

To estimate uncertainties of our measurements, we followed the method proposed by *Clarke et al.* [2011] and performed a synthetic test on the L'Aquila noise cross-correlations. We perturbed the reference cross-correlation function by stretching its waveform and simulating different values of velocity variations (from 0.01% to 0.5%). Then, we added a random noise with a signal-to-noise ratio of 5 (that is the mean value measured from the observed cross-correlations). Finally, we applied the MWCS technique to measure the apparent velocity variations $\frac{\Delta v}{v}$ between the perturbed cross-correlations and the original CC^R. The RMS deviations between the estimated velocity variations and those introduced through stretching characterize the uncertainties of our measurements.

To investigate the depth extent of the measured crustal velocity perturbations, we performed the MWCS analysis inside three different frequency bands: [0.1–1], [0.1–0.6], and [0.5–1] Hz. It has been shown both theoretically and observationally that at these frequencies the coda of seismograms and correlation functions are mainly composed of surface waves [e.g., *Hennino et al.*, 2001; *Margerin et al.*, 2009]. We therefore expect that the sensitivity of the coda waves to a velocity change at depth depends on their spectral content with shorter periods sensitive to shallower structures and longer periods sampling deeper parts of the crust. The measurement results for the three frequency bands are presented in **Figure 3** and show a sudden velocity decrease at the time of occurrence of the L'Aquila main shock. The amplitude of this velocity drop is largest at frequencies higher than 0.5 Hz and decreases at lower frequencies. This indicates that a large part of the observed variations have their likely origin within the shallow crustal layers.

4. Discussion

A limited number of available stations (only three) and the fact that only one of them is located in the immediate vicinity of the earthquake fault did not allow us to identify exact regions that produced the observed velocity variations. Also, the dataset used in this study did not allow us to make robust measurements with refined time resolution. A denser network covering the source area would be required to obtain better space and time resolutions [e.g., *Brenguier et al.*, 2008a]. Therefore, we interpret here only the most robust average features.

The results presented in our study show that the L'Aquila main shock caused a detectable reduction of seismic velocities within the surrounding crust. We observe that the velocity dropped by 0.3%, which is more than 3 times larger than the fluctuations observed before the main shock. Co-seismic velocity reductions can be attributed to increasing crack and void densities in the shallow crustal structure and/or to reduced compaction of the near-surface granular material. The presence and migration of fluids can further contribute to modification of the seismic properties in the shallow crust. Our results can be compared with other studies that have addressed changes of the crustal parameters prior and after the L'Aquila earthquake. *Amoruso and Crescentini* [2010] used strain measurements obtained in the Gran Sasso laboratory during the two years prior to the main shock to infer that no anomalous signal was observed. They concluded that the possible earthquake nucleation zone was confined to a volume less than 100 km^3. In contrast, v_p/v_s anomalies have been reported by *Di Luccio et al.* [2010] in the weeks prior to the main shock with an abrupt variation after the $M_L = 4.1$ foreshock occured on March 30. Similar results were obtained by *Lucente et al.* [2010] who used shear wave splitting in addition to v_p/v_s ratios. They attribute the velocity anomalies occurring in the week prior to the main shock to a complex sequence of dilatancy-diffusion processes in which fluids play a key role. *Terakawa et al.* [2010] inverted the stress field obtained from the aftershock sequence focal mechanisms to determine the fluid pressure and to conclude that the spatial pattern of the sequence is driven mainly by fluid migration.

Our results are based on current cross-correlation functions stacked over a 50 day period and, therefore, do not have the time resolution required to identify possible short-term precursory variations and to separate them from the co-seismic effect. On the other hand, with stacking large data volumes our estimation of the co-seismic velocity reduction is inherently very robust. The observed velocity reduction is larger at higher frequencies. Therefore, we prefer the hypothesis the perturbation is mainly due to damaging of shallow soft sedimentary layers by the co-seismic strong ground motion [e.g., *Wu et al.*, 2009]. This effect may be also enhanced by the presence of fluids.

We compare the co-seismic perturbation observed during the L'Aquila earthquakes with other cases when the co-seismic crustal velocity variations were measured from noise cross-correlations (Table 2). The co-seismic velocity drop measured for the L'Aquila earthquake ($\sim 0.3\%$) is significantly larger than the values measured within a similar frequency band for the M_W 6.0 Parkfield and the M_W 7.9 Wenchuan events ($\Delta v/v \sim 0.08\%$ as reported by

Brenguier et al. [2008a] and *Chen et al.* [2010], respectively). At the same time, a stronger variation ($\sim 0.6\%$) has been observed **with** the stretching technique and frequencies higher than 2 Hz during the M_W 6.6 Mid-Niigata earthquake. The results of this comparison suggest that the level of measured co-seismic velocity variation is not a simple function of the total moment release during an earthquake but is controlled by different factors such as local geological conditions and, possibly, focal mechanism and source depth. Also, the frequency range used in the analysis controls the depth extent of the measured anomaly. Finally, the aperture of the used seismic network (i.e., the distance between the station pairs) can play an important role. So far, the velocity variations reported in this study were measured over a relatively large area. Therefore, they may be less sensitive to the processes occurring in the immediate vicinity of the fault, where stress-induced velocity perturbations are expected to be most important.

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Table 1. Parameters of the three inter-stations paths used in the study. The Rayleigh wave arrival times are roughly estimated considering a group velocity of 3 km/s [*Chiarabba et al.*, 2009]). Parts of the correlation functions with group velocities faster than 2.5 km/s we excluded from the analysis to avoid the influence of the noise source variability in direct arrivals.

stations	distance km	Rayleigh arrival s	cutoff s
AQU_CAMP	20	6.67	±7.5
AQU_FIAM	26	8.67	±10
CAMP_FIAM	38	12.67	±15

Table 2. Comparison between the L'Aquila event and other earthquakes where co-seismic velocity variations were measured from noise cross-correlations. Values of velocity variations are from *Brenguier et al.* [2008a], *Wegler and Sens-Schönfelder* [2007], and *Chen et al.* [2010], for the Parkfield, the Mid-Niigata, and the Wenchuan earthquakes, respectively.

Earthquake	M_w	depth km	focal mechanism	$\Delta v/v$ %	frequency Hz	stations
L'Aquila	6.1	8.8	normal	0.15	0.1–0.6	3
				0.3	0.1–1	
				0.4	0.5–1	
Parkfield	6.0	7.9	strike-slip	0.08	0.1–0.9	13
Mid-Niigata	6.6	5	thrust	0.6	> 2	1
Wenchuan	7.9	19	thrust	0.08	0.3–1	> 30

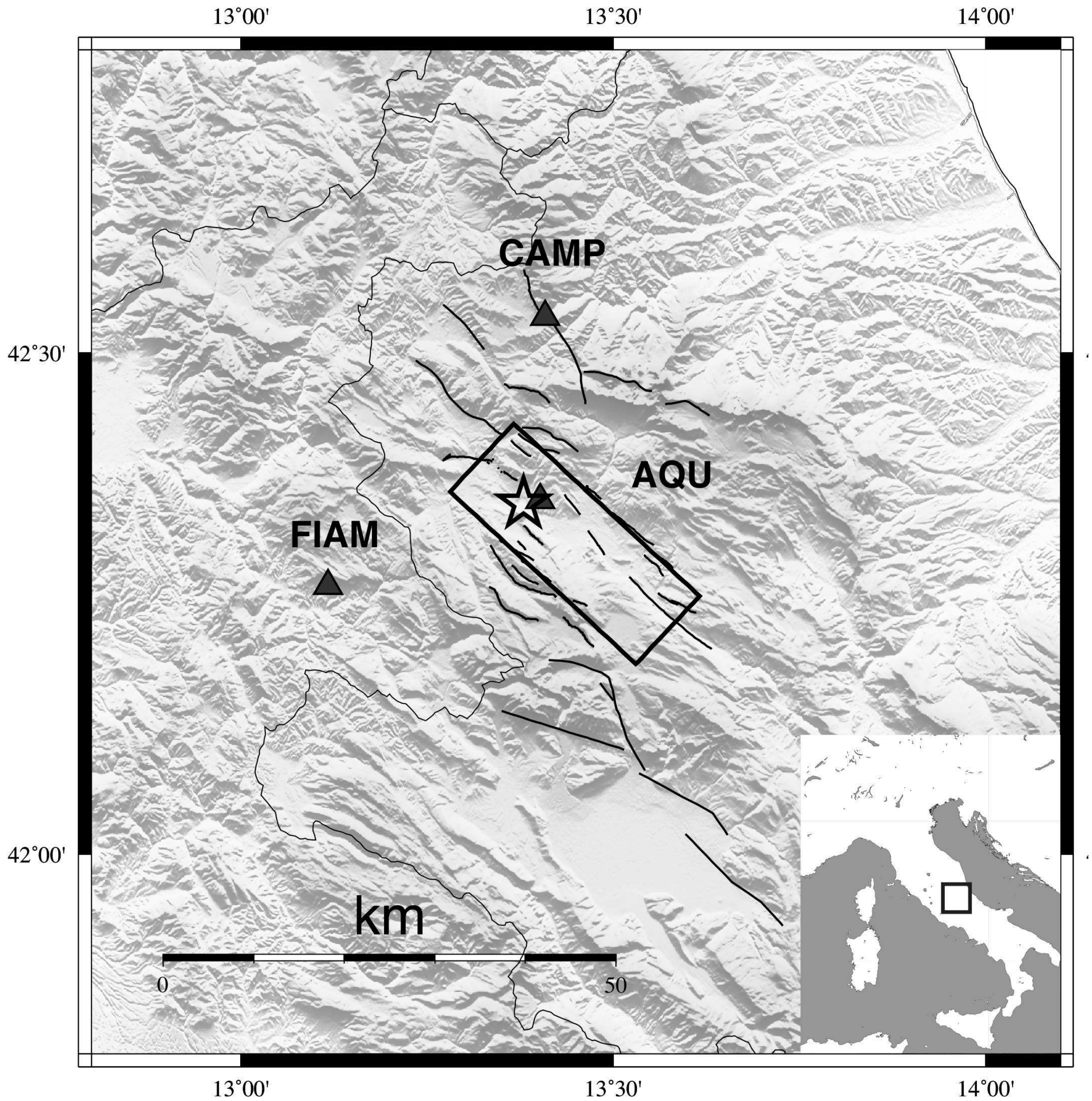

Figure 1. Map of the central Apennines showing the location of the L'Aquila epicenter (black open star) and of the fault plane projection (black rectangle) from *Cirella et al.* [2009]. The gray triangles are the three stations considered in this study. Black thin lines indicate main tectonic faults from *Emergeo Working Group* [2010]. Light gray lines show the regional boundaries.

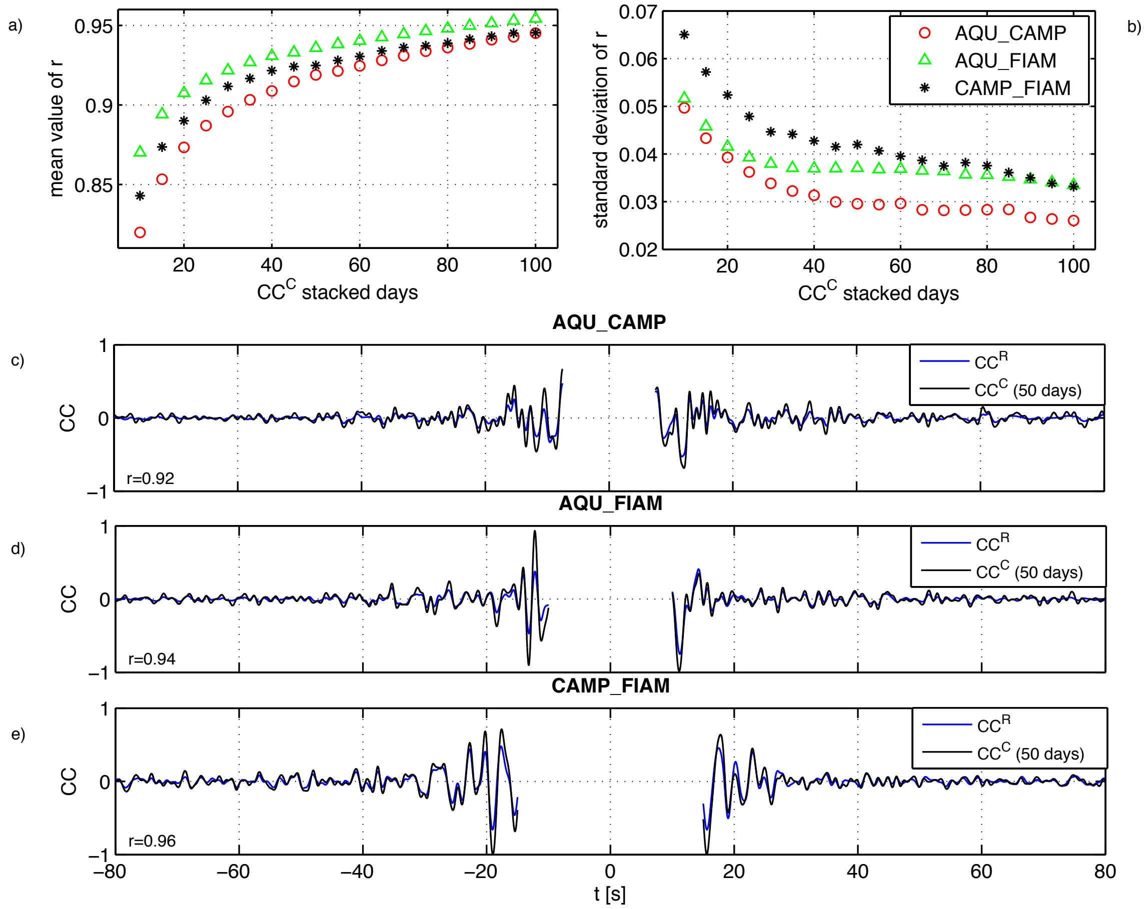

Figure 2. Mean (a) and standard deviation (b) values of the correlation coefficients r between CC^C and CC^R as a function of number of days used to construct the current correlation functions CC^C. Mean and standard deviations were computed after a Fisher transformation that returns an almost normally distributed variable [*VanDecar and Crosson*, 1990]. Panels (c),(d), and (e) show the reference cross-correlation functions CC^R(blue) together with an example of 50 day current function CC^C (black) for the three couples of stations. Only portions of the the signal considered in the analysis are plotted (Table 1). Numbers in the bottom left corners are the respective correlation coefficients r.

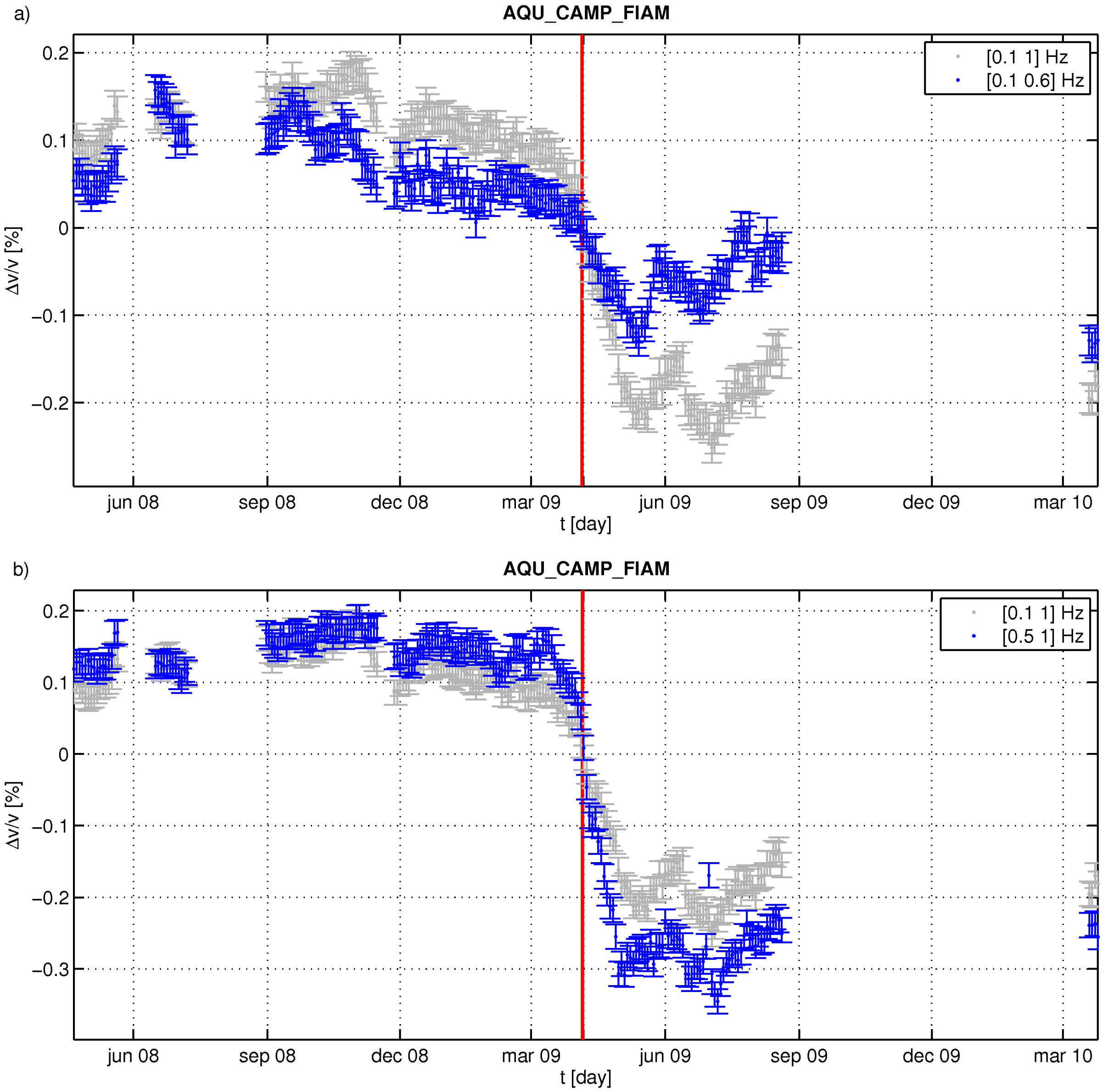

Figure 3. Relative velocity variations measured from cross-correlations of seismic noise recorded at the three stations (gaps correspond to periods when the stations were not operating simultaneously). Results obtained by analyzing the whole frequency range [0.1 1] Hz are shown with a gray color. Blue color shows the results from narrower frequency ranges: (a) [0.1 0.6] Hz and (b) [0.5 1] Hz). Vertical bars indicate the uncertainties of the measurements. The vertical red line highlights the time of occurrence of the L'Aquila main shock.